Design of a High Performance Energy Coupling Actuated Valve (ECAV)

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Abstract

Most commercially available valves are able to produce a large flow rate or a fast response, but are incapable of producing both simultaneously. Commercially available valves that can achieve both are expensive as they require multiple stages of actuation and piloting pressures to deliver large flow rates quickly, preventing them from being broadly used in fluid power applications. This work investigates the design of an Energy Coupling Actuated Valve (ECAV) that is capable of solving this trade-off between large flow and fast switching times through the use of an innovative, high performance actuation system. The ECAV is a new development in valve technology in the area of hydraulic, high speed, proportional and digital on/off valves. High speed actuation is produced through the intermittent coupling of a kinetic energy source with a translational poppet or spool. This coupling process occurs through the use of magnetorheological fluid and a controlled magnetic flux through the fluid in the energy coupler. The ECAV has several design advantages including proportional force control and a large (7mm) stroke capability. Early results predict a nominal flow rate of 100 L/min at a 5 bar pressure drop can be achieved with a 3 ms on/off response time.

KEYWORDS: High performance valve, actuation technology, digital, on/off, proportional

1. Introduction

Hydraulic systems are widely used in industry for control and transmission of power using high pressure fluids. Benefits of hydraulics include high power-to-weight ratio, controllability, high torque, and ability to flexibly transmit hydraulic fluids over long distances. Hydraulic applications can be divided into three main areas: mobile, industrial, and aerospace hydraulics.

According to a study conducted by the Department of Energy (DOE), fluid power systems account for 2 to 3 percent of the total energy consumed in the United States /1/. However, the average efficiency in mobile hydraulic applications is around 21%, consuming between 0.36 and 1.26 Quads/year /2/. A small increase in the efficiency of hydraulic systems would lead to significant energy savings in the United States, and globally.

To identify the main sources of inefficiencies, a breakdown of the major components in hydraulic systems is shown in Figure 1. According to the DOE study, energy losses in mobile hydraulic systems can be mainly attributed to:

1. Transmission line losses when transferring power from the engine to the hydraulic pump
2. Pump losses
    a. Friction and leakages
    b. Low efficiency when running at low displacements and at non-ideal running conditions
3. Line losses which are mainly head losses at couplings
4. Valve losses
    a. Internal leakage
    b. Metering losses due to pressure drop across the valve
    c. Slow delay and transition response times
5. Load losses due to the oscillation of the weight being moved, forcing fluctuations in the power supplied by the engine, impacting efficiency.

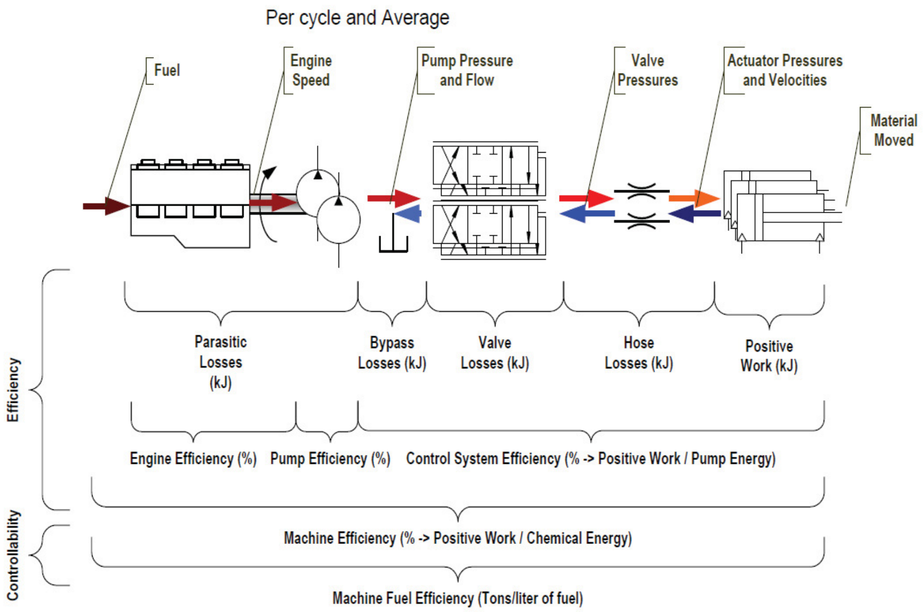

Figure 1: Hydraulic system losses, /2/.

Figure 2 shows the breakdown of losses in mobile load sensing hydraulic applications. The main losses are the valve losses, actuator work, charge, friction, and pump losses; valve losses stand out with the highest losses, constituting to 43% of the total losses.

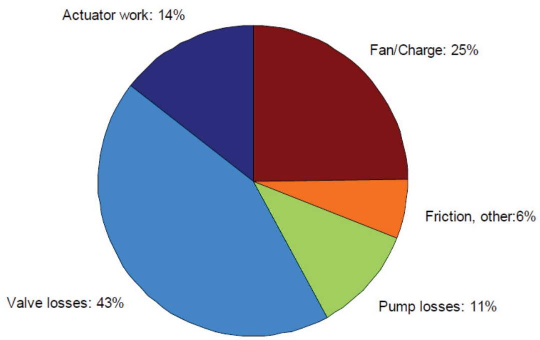

Figure 2: Energy losses in mobile load sensing hydraulic application, /2/.

Given the significant losses attributed to the performance of the valves and the need for valves in almost every hydraulic system, new valve configurations aiming at enhanced performance have been proposed in literature /3/; /4/; /5/; /6/; /7/. Some of these include using new valve concepts such as using a rotational energy source /3/; /8/; /9/; /10/. Other work included modifying the valve signal by using a peak-and-hold and reverse current strategy to improve the valve response time /11/. This work introduces an innovative high performance valve design that aims to overcome the limitation of commercially available valves.

2. Background

2.1. High Performance Valves

High speed valves are an integral component in hydraulics. Valves can improve the performance of current fluid power systems by offering higher bandwidth valve control, higher flow rate, and higher actuation speed. Valves that are capable of both high flow rate and high actuation speed can improve system efficiency by reducing the valve inefficiencies detailed in the introduction. This is accomplished through decreasing the amount of time the valve is metering the flow and reducing slow transition times that come with slower actuation valves. This concept is utilized in on/off valve systems. In traditional valve systems, energy is lost as a result of valve transition times and opening area of the valve /12/. Therefore, a higher performance valve can lead to energy efficiency savings.

High performance valves also are a key enabler for digital fluid power systems. Digital fluid power systems require fast switching techniques to control on/off valves for different operating strategies. According to Yang, /13/, modern valve design approaches have developed rapidly over the past few decades and new designs for high bandwidth valves are desired in this field to meet the switching requirements. Research has led to new innovations in high performance valve actuation.

2.2. Comparison of High Speed Valve Actuation Mechanisms

Hydraulic valve control is achieved through a variety of actuation methods and technologies. High performance valves often utilize multiple stages of actuation or an advanced electro–mechanical control structure. Solenoid valves are widely used in industry for their reliable performance. Research in solenoid valve technology has further optimized the dynamic response of the solenoid through varying control strategies and performance evaluations /14/; /15/. However, this research has limitations due to the large mass acceleration profile and rapid force fall-off that is inherent with a solenoid valve. Parker Hannifin produced a voice coil valve that is capable of proportional control for a fast response. It can deliver a force of 100 N with flow rates up to 40 lpm at a 35 bar pressure drop /16/. The main advancement in voice coils compared against solenoid valves is that the actuation mass is much smaller when compared to the solenoid actuation plunger that has to accelerate and decelerate during each actuation.

Piezoelectric actuation is used for its fast response frequencies and research in this area has led to improving the technology's limited stroke capability, yet more work in reducing electrical power consumption is needed /17/. Servo valves offer a precise control of position while delivering high flows in a quick response. A servo valve's design utilizes multiple stages with high tolerance metering edges that increase the price of the valve as well as making it prone to contamination issues.

3. Energy Coupling Actuator (ECA)

The high speed actuation method investigated here is produced through the coupling of a rotating mass to a normally stationary mass. The energy transfer between the two masses causes the translational mass to rapidly accelerate. The rotating mass acts as a momentary source of kinetic energy, represented by a spinning, slotted disk connected to a rotating shaft in Figure 3. The rotating disk can be powered by an electric motor or by a belt reduction off an engine or pump shaft. The stationary mass is a low weight, translational piece with magnetic coils that lies in a slot inside the disk and is connected to a poppet or spool assembly. This design separates the large energy source mass from the light weight actuation mass, similar to the voice coil valve design. This allows for a faster acceleration and deceleration profile while operating at lower power amounts than would be necessary to move the larger combined mass.

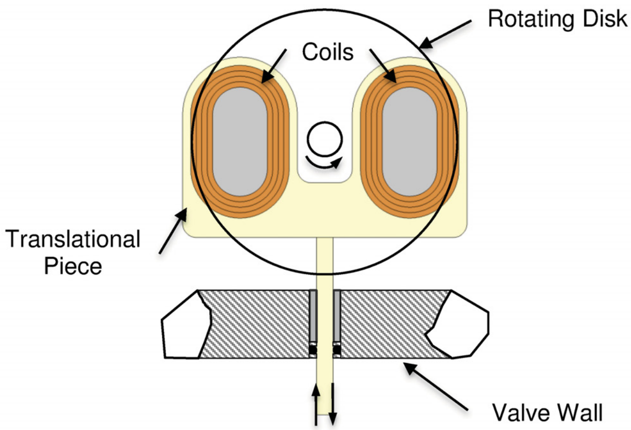

Figure 3: Section view of the energy coupling actuator (ECA) assembly, /18/

These two pieces are immersed in magnetorheological (MR) fluid. By controlling the magnetic flux density inside the system through energizing the coils attached to the translational piece, the MR fluid gap between the spinning disk and the translational piece transforms from a liquid to a solid creating a shear force between the two pieces.

This liquid-solid conversion is completely reversible and has a conversion period within a millisecond /19/. The shear force generated is proportional to the magnetic field strength existing in the system. The ECA has two surfaces in shear with the rotating disk, increasing the shear force generation. The actuation force generated through the MR fluid shearing is a net upwards or downwards force dependent upon which coil set is currently active. The actuator position is controlled through the quick fluid clutching connection as energy is transferred from the source to the translational piece. The actuating mechanism has been designed, simulated, prototyped, and tested /18/. Figure 4 details the simulation and experimental results of the displacement profile for the ECA. A peak and hold strategy was utilized to reach a 1.5 mm displacement in 3 ms. A large stroke capability was demonstrated as 7 mm displacement was reached in under 7 ms.

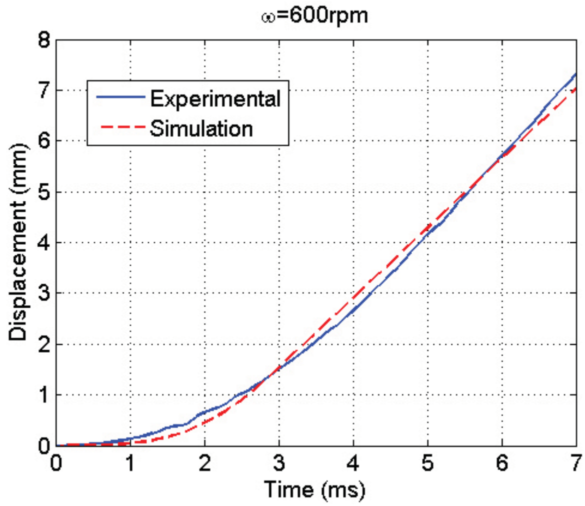

Figure 4: ECA displacement vs. time, /18/

4. Energy Coupling Actuated Valve (ECAV)

Incorporating the ECA into a valve aims at solving the trade-off often seen when trying to simultaneously achieve a large flow rate in a fast operating valve. There are several design advantages for an ECAV. Firstly, either port of the valve can be under high pressure. This makes the valve capable of two way actuation regardless of the system flow direction. The ECAV does not require piloting pressures (but does require an external source to spin the disk; i.e. electric motor, engine shaft, etc.). This external pressure source has been replaced by a rotary energy source (slotted disk). The poppet valve assembly utilizes a positive poppet seal between the poppet and the valve wall to minimize leakage across ports. However, the valve isn’t limited to a poppet type valve, a spool configuration is also capable in this design. The ECAV is capable of generating a long stroke (7 mm) while offering a proportional, bidirectional actuation force that is both large (100 N) and scalable /9/. Lastly, as seen in Figure 5, the ECAV can have multiple ECAs along a common shaft powered by the same motor or pump shaft for systems that require large amounts of flow. Aligned like this saves space as well as allowing each actuator to be independently controlled if needed.

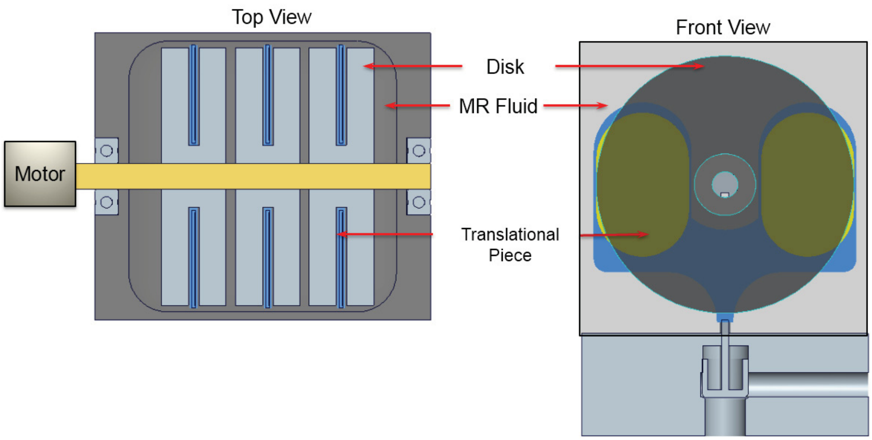

Figure 5: Stacked valve configuration

4.1. Poppet Assembly

The poppet type valve has been designed in CFD to achieve a 100 lpm flow rate at a 5 bar pressure drop across the valve. Figure 6 shows the poppet assembly inside a valve block with a spring to hold the poppet closed.

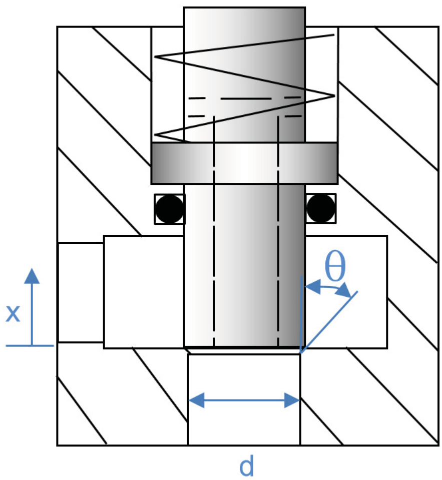

Figure 6: Poppet assembly

When displacements are small, the flow area for the valve is given in (1)

$$A_{flow} = \pi d x \sin\theta \left\{1 - \frac{x}{2d}\sin 2\theta\right\} \quad (1)$$

Flow forces are the main concern when designing a direct acting poppet valve. For this reason, the poppet has been designed to be statically pressure balanced such that the area on the spring side of the poppet is equal to the area on the seat side of the poppet. The two sides share the same pressure so the forces balance out. This design requires high pressure seals to separate the high pressure fluid from the outlet port and the MR fluid region in the translational actuator assembly. The poppet rod extends outside of the valve block to attach rigidly to the translational piece. Figure 7 shows a detailed section view inside the poppet valve assembly, showing half of the rotating disk along with the translational piece assembled to the poppet valve block.

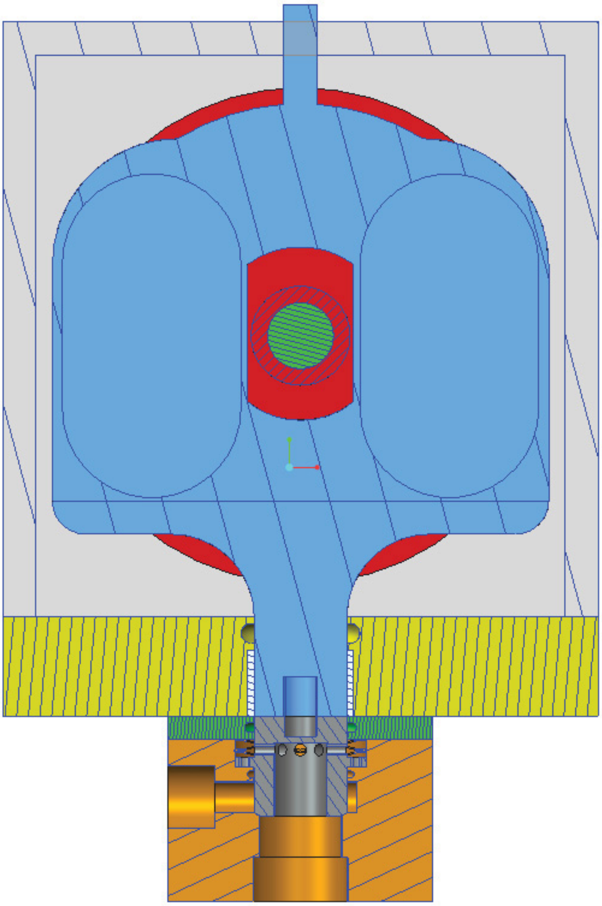

Figure 7: Section view of the poppet valve assembly

A sleeve bearing supports the translational piece and poppet attachment. Atmospheric pressure seals are needed above the sleeve bearing and in the MR fluid box to separate the MR fluid from the hydraulic fluid. This part of the assembly does not see any pressure.

4.2. Spool Assembly

Testing of the ECA will also be done on a spool type valve. Spool valves are less affected by flow forces due to their balanced design, however, are more prone to leakage if poorly manufactured. Due to this concern, a cartridge spool type valve from Sun Hydraulics was selected to be modified to fit the ECA as it would have the industry clearances for sealing. A layout of the assembly can be seen in Figure 8.

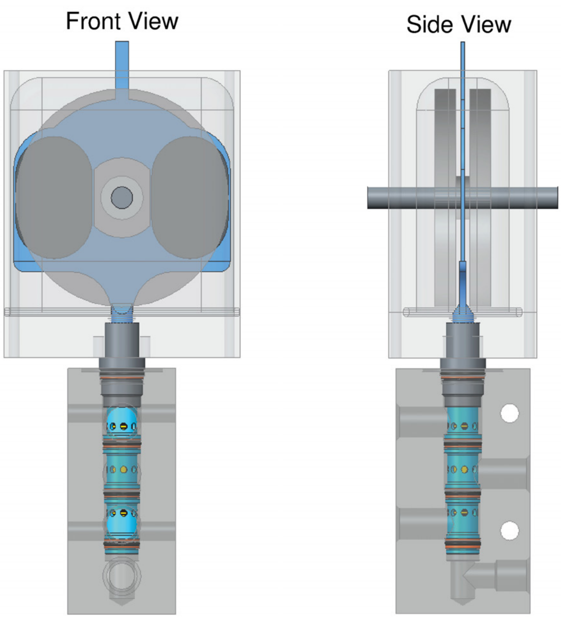

Figure 8: Spool assembly

The DCDCXCN model spool from Sun Hydraulics, /20/ was selected due to it’s hollow spool design. A valve plate and seal will need to be installed inbetween the actuator assembly and the valve assembly that will see hydraulic fluid at tank pressure.

4.3. Experimental Testing

For both prototypes, the translational piece extends out of the top of the MR fluid box for position feedback and control. Figure 9 depicts the layout of the experimental system. A position sensor measures the tab that exits from the actuator translational piece and the measured position is sent to a controller which then modulates a driver circuit to change the magnetic flux density in the translational piece assembly.

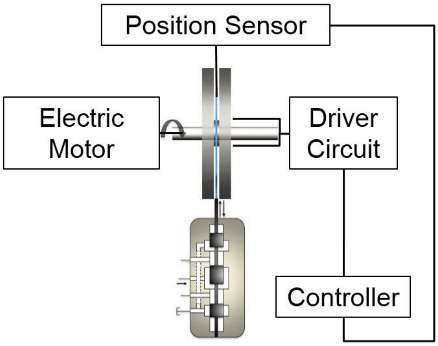

Figure 9: Electrical system for position control

5. Conclusion

High performance valves are a crucial component in fluid power systems. Research is being done on new ways of valve actuation to achieve higher system efficiencies as well as faster responses to meet the growing demand of high performance fluid power systems. This paper introduced the design of an energy coupling actuated valve that separates the actuation mass from the energy source mass to develop a faster dynamic response. Design advantages include long stroke capabilities, bidirectional proportional force control, compact stack configurations, and it doesn't required a pilot pressure. Two valve assemblies were investigated and compared. Challenges to implementation of these valves will come with developing the controller and driver circuit.

6. Acknowledgements

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8. Nomenclature

d	Poppet Diameter	mm
x	Poppet Stroke	mm
θ	Half Angle of Poppet	degrees